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PROVISIONAL APPLICATION COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION under 37 CFR 1.53(c).

Docket Number	10630-18	Type a plus sign (+) inside this box	+

INVENTOR(S)/APPLICANT(S)

Last Name	First Name	Middle Initial	Residence (City And Either State Or Foreign Country
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TITLE OF INVENTION (280 characters max)

PLASMA BEAM SOURCE

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ENCLOSED APPLICATION PARTS (check all that apply)

☒ Specification Number of Pages 11 ☒ Small Entity Statement
☒ Drawing(s) Number of Sheets 10 ☐ Other (specify) ____

METHOD OF PAYMENT (check one)

	PROVISIONAL FILING FEE AMOUNT(S)	
☒ A check or money order is enclosed to cover the Provisional filing fees. ☒ The Director is hereby authorized to charge any deficiency in the filing fees or credit any overpayment to Deposit Account Number 23-1925		80.00

The invention was made by an agency of the United States Government or under a contract with an Agency of the United States Government

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Respectfully submitted,

SIGNATURE: Susan D. Reinecke
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Date: September
Registration No. 40,198
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☐ Additional inventors are being named on separately numbered sheets attached hereto.

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Our Case No.10630/18

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
PROVISIONAL APPLICATION FOR UNITED STATES LETTERS PATENT

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TITLE: PLASMA BEAM SOURCE

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PLASMA BEAM SOURCE

BACKGROUND

The present invention relates to plasma sources used for industrial processes such as plasma treatment, plasma enhanced chemical vapor deposition (PECVD) and plasma etching and to electric propulsion devices for space applications.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a section view of a beam source.

FIG. 2 shows a top section view of the apparatus of FIG. 1.

FIG. 3 shows an isometric view of the apparatus of FIG. 1.

FIG. 4 shows a view of the beam source with the beam directed toward a substrate and separate gas inlets

FIG. 5 shows a view of a beam source used to assist reactive deposition in an electron beam evaporation application.

FIG. 6 shows a side view of a beam source applied to a planetary/box coating application

FIG. 7 shows a beam source with the plasma directed onto a translating, biased substrate.

FIG. 8 shows two beam sources facing each other with opposite pole magnets

FIG. 9 shows a section view of an electromagnet version of the present invention for a space thruster application

FIG. 10 shows a preferred embodiment with an electrical power arrangement enhancing the ion source aspects of the present invention.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

FIG. 1 shows a section view of the beam source 24 producing a beam of dense plasma 9 projecting from nozzle 6. The source resides in a vacuum chamber not shown. Magnets 1 and 2 are disposed facing each other with the south poles supported by mild steel shunt 3. The magnets 1 and 2 produce a cusp magnetic field composed of outwardly directed field lines 18 and inwardly directed lines 19. The inward lines 19 pass through insulator 15 and liner 16 to center shunt 10. Along with end magnets not shown and magnets 1 and 2, the cusp fields 18 and 19 create endless electron traps in regions 9 and 8. Shunt 10 is connected to shunt 11, and both are made of mild steel. Liner 16 is brazed to block 12 to improve heat transfer. Block 12 is water cooled via gun drilled holes 13 and piping not shown. Shunt 11 is fastened to block 12. The assembly of the liner 16, block 12 and shunts 10 and 11 form one electrode of the source. The second electrode is formed by shunt box 3 and cover 5. The magnets are ceramic type isolated from liner 16 and block 12 by insulating pieces14 and 15. Insulating pieces 14 and 15 can be fabricated from fluoropolymer. Gaps of approximately 3mm 100 separate box 3 from block 12 and shunt 11 to eliminate plasma in the gap. Gas is brought into the source through port 4 in box 3. The gas travels around block 12 in the gap 100 between box 3 and block 12. Gas then flows into multiple thin trenches 22 cut into box 3 and cover 5. Gas exits into the central source area between cover 5 and liner 16. Cover 5 includes a nozzle 6 though which the gas flows into the vacuum chamber. The cover 5 and nozzle 6 are water cooled with brazed-on tubing 7. Power supply 17 is connected on one side to cover 5, box 3 and to chamber ground. The other power supply 17 pole is connected to internal block assembly 12 (and consequently liner 16 and shunts 10 and 11). The electrical connection to block 12 is made to the water cooling tubing exiting box 3 (tubing not shown). Power supply 17 can be a standard sputter magnetron type or be a pulsed DC, mid-frequency AC or RF supply. In this FIGURE a DC supply 17 is used with the negative electrode connected to

block 12. When a gas is introduced into source 24 and power supply 17 is turned on, a plasma is ignited in regions 8 and 9 of the source. Region 8 is an endless Hall current contained plasma extending the length of the source. The two lobes of region 8, as seen in section view FIG. 1, appear as an extended donut of plasma when the inside of the operating source is viewed. This region 8 is created when the electric field from cover 5 penetrates down past magnetic field lines 19 inside the source. As electrons attempt to follow these electric field lines they are restricted by magnetic field lines 19. As is known in many other Hall current contained sources such as sputter magnetrons or closed drift ion sources, electrons cannot escape from the electrostatically and magnetically confined region made by electron containing liner 16 and shunt 10 surfaces and field lines 19. The result is a confined plasma region 8 inside the source 24. Region 9 is created and sustained as a fortuitous result of plasma 8. By the arrangement of magnetic field lines 18, cover 5 and nozzle 6, electrons created by plasma 8 are prevented from reaching the cover 5 and nozzle 6 anode electrode. As can be seen, field lines 18 pass out of liner 16, converge and exit through nozzle 6. Since electrons cannot cross magnetic field lines, the electric circuit between cover 5, nozzle 6 and plasma 8 can only be completed by the electrons exiting through nozzle 6 and passing out of the magnetic field 18 containment region. Plasma 9 is created because, when electrons attempt to escape along magnetic field lines 18 through the nozzle 6, they are confronted with a magnetic mirror as field lines 18 converge in nozzle 6. This mirror region reflects a portion of the electrons and creates a second containment region 39 within plasma 9. Region 39 is again a closed drift magnetic bottle as electrons move in a cyclodial motion down to one end of the source and back to the other. This second containment region 39 then ionizes the gas flowing through nozzle 6. This mechanism creates a dense plasma 9 that extends out of nozzle 6 into the vacuum chamber. When the source 24 is viewed in operation, it appears that plasma 39 and plasma 9 are one plasma.

FIG. 2 shows a top view of the beam source 24 depicted in FIG. 1 with cover 5 removed. This view shows end magnets 20 and 21 that along with side magnets 1 and 2 create the closed drift magnetic fields 18 and 19 (only 18 shown in this view). Also visible are box 3, liner 16, insulators 15 and, below magnets 1,2, 20 and 21, water cooled block 12. Plasma 9 is shown as the darker portion exiting the source. The lighter portion is inside the source and corresponds to plasma region 39.

FIG. 3 shows and isometric view of the beam source 24 depicted in FIGS. 1 and 2. Water cooling piping is not shown. (The water piping is useful to also make electrical connections to both electrodes.) In this view, plasma 9 is seen emanating out of nozzle 6. As shown, the plasma 9 forms a narrow uniform beam fanning out from nozzle 6.

As will be readily known to one skilled in the art, the beam source 24 may take on many shapes, sizes, scales and be constructed of different materials. The source of FIGS. 1-3 was constructed as follows: Magnets 1 and 2 are ceramic type measuring 1" wide x 4" long x 1" thick. Magnets 20 and 21 are 2" long of the same other dimensions. Box 3 is made of .25" thick mild steel plates. Block 12 is brass. Top cover 5 and nozzle 6 are copper. The opening in nozzle 6 is .75" wide x .75" deep x 3.5" long. Shunt 10 is mild steel as is shunt 11. The liner 16 material is copper sheet bent into an oval shape and the distance between the inside walls of liner 16 is 1.5". Again, while the source as detailed is the present embodiment, many variations and modifications can be made without overstepping the inventive advancement of the source.

The beam source and the plasma 9 have several interesting and useful properties ~~:~~ as indicated by the following measured values

- Plasma 9 is very dense, with ion densities exceeding 10^+12 per cm^3 for a DC power supply output of 1 kW at ~300V. The ion saturation current was measured at over 100mA for the source dimensions given and these power supply settings. (The current probe surface was positioned 5 cm beyond the end of nozzle 6 blocking plasma 9.) Electron current with the probe grounded is greater than 1 A.

- As with sputter magnetrons and other Hall current confined sources, the plasma 9 tends to be uniform over the length of the source (minus end effects at the turnarounds). This is important for all applications where uniformity of deposition, treatment or etching is required (as it is in most applications). Substrate widths of 3 meters or more can be uniformly processed. In operation, plasma 9 appears as a ~one cm wide uniform beam projecting out of nozzle 6.
- The plasma beam source ("PBS") is not a sputter source. The purpose of the source is for PECVD, plasma treatment or etching processes. While sputtering of the liner material does occur, only minimal sputtered material exits the nozzle. This is due to at least two factors: The magnetron plasma region 8 (referring to FIG. 1) is located deep inside the source. Sputtered liner material redeposits on the liner, the shunts 10 and 11 or on the cover 5 and nozzle 6. Since the sputtered material readily condenses on contact with a surface, the design produces a 'torturous path' for sputtered material attempting to exit the source. Secondly, by feeding process gas in above magnetron plasma 8, the flow of supply gas to the plasma 8 is directed away from nozzle 6, creating directional momentum effects opposing condensate flow out of nozzle 6. The low sputter rate of the source is seen in operation. For instance, in depositing a PECVD Silicon Oxide coating, while several microns of coating are deposited, the resulting coating is optically clear. This result was obtained using a copper liner 16. Sputtered copper in oxygen and argon gas shows up as a black coating. This is not visible on the substrate.
- Pure reactive gas can be 'burned' in this source. Many high density plasma sources implement filaments, low work function materials or field effect devices to generate electrons. These sources typically feed an inert gas such as argon into the source. Use of a reactive gas such as oxygen inside the source tends to greatly shorten electron source lifetime. To accomplish a reactive process, these sources feed oxygen outside the source, reacting a portion of the oxygen with the argon plasma exiting the source. While the efficiency of this method is low, it is used today in many processes because no alternative exists. The beam source changes this with the ability to directly produce a high density, pure oxygen plasma. This has advantages to several processes. The vacuum pumping requirements are also reduced as the argon flow requirements for the source are not needed.
- The beam source can be operated over a wide range of process pressures. As is typical for magnetron type sources, the PBS can readily operate at pressures in the 1-100mTorr region. In addition to this pressure range, operation can be extended down to the range used in evaporation processes. This can be done because of nozzle 6 limits gas

conductance out of the source. By feeding the process gas through the source into the chamber, the pressure inside the source can be sustained in the mTorr region while outside the process appropriate pressure is maintained. This allows the process region to maintain the long free mean paths needed for operations such as thermal or electron beam evaporation. Also, process gas flow requirements are minimized by the high ionization efficiency of the beam source.

- The plasma beam 9 extends for 100's of mm from nozzle 6 depending upon the free mean path inside the vacuum chamber. At 3mtorr for instance, the beam extends at least 300mm. This property allows the beam source to excel at many applications. For instance, non-planar substrates can be uniformly PECVD coated, treated, etc..
- The substrate can be electrically isolated from the beam source 24. Because the substrate is not part of the electrical circuit, the substrate can remain floating or be separately biased by a different power supply. This feature is presented in later FIGS.
- The beam source 24 operates using standard magnetron power supplies and at a variety of frequencies. DC or AC from 0-100MHz frequencies can be used. Special high voltage power supplies or RF supplies do not have to be used. The connection to chamber ground can also be made to either side of the power supply. In FIGS. 1-3, box 3 and cover 5 are connected to ground. This is convenient because less high voltage is exposed to the chamber (safety) and mounting is made easier.

FIG. 4 shows a beam source 24 in a PECVD coating application. A mixture of argon and oxygen 41 are delivered to source port 4 in tube 40. A monomer precursor gas 43 is dispensed outside the source. A coating is deposited onto substrate 23 when the precursor gas is activated by the ionized gas in plasma 9. This process highlights another advantage of the present invention: Due to the conductance limitation of nozzle 6 and to the high density and directionality of the plasma 9 exiting through the nozzle 5, the precursor gas 43 does not readily enter source 24. This can be seen when after a coating run the inside of the beam source 24 is relatively free of PECVD coating. The substrate 23 can be a multitude of materials and shapes. Flexible webs, flat glass, three dimensional shapes, metals, silicon wafers to name a few.

Many other physical and process configurations are possible with the beam source 24. For instance, precursor gases can be ported into the source

without immediate buildup problems and some gases such as hydrocarbons can be fed into the source for extended periods. The beam source can also perform many plasma processes beyond PECVD such as plasma treatment, surface cleaning or reactive ion etching.

FIG. 5 shows the beam source 24 used to react evaporant 29 in an electron beam evaporation web coating application. Drum 25 carries web 23 over the deposition region. Crucible 27 contains evaporant material 28. Electron beam source 26 emits beam 31 into crucible 27. Beam source 24 plasma 9 is directed into the evaporant cloud 29 to promote reaction with the ionized gas of the plasma 9. A shield 30 limits the effect of the plasma 9 on the electron beam 31. Prior to the present invention, complicated hollow cathode sources have been used to accomplish evaporant reactance. Hollow cathodes are inherently non-uniform as diffusion of the plasma outside of the hollow cathode is not limited. With the beam source, the magnetic field lines 19 contain the electrons, and by electrostatic forces, the ions are likewise contained in plasma region 9. Also as described above, the beam source plasma 9 is uniform over the substrate width due to the closed drift nature of electron containment.

FIG. 6 depicts the beam source 24 applied to a planetary box coater application. In this view the source 24 is shown along it's length rather than from an end view. In this view the plasma beam 9 appears as a sheet of plasma. The source 24 is placed distant from the substrate supporting planetary, say at the bottom of the box coater, and allows room for other deposition sources (electron beam or thermal evaporation sources for instance. By combining the beam source 24 with other deposition sources the coatings can be densified by the action of plasma 9. Pure argon can be used to densify a metal coating or a reactive gas can be added. A big benefit of the beam source over prior art in these applications is the ability of the beam source to directly consume reactive gases such as oxygen in the source. Prior art, due to the need for filaments or other electron generation means sensitive to consumption by reactive gas,

required the use of an inert gas in the source.

In these sources, the reactive gas was fed into the process outside the source. The poor efficiency of ionizing the reactive gas in the chamber requires high source powers and high argon flow rates. With the beam source 24 producing a pure reactive plasma (or a combination of inert and reactive as required) the process efficiency is increased and the overall pumping speed needed to maintain the process at the correct pressure is reduced. (The un-needed argon does not have to be pumped away.)

FIG. 7 shows beam source 24 applied to a substrate 23 such as a silicon wafer. In this figure, the stage 51 supporting the wafer 23 is translated to uniformly treat wafer 23 with plasma 9. The ability to separately bias substrate 23 from source 24 is depicted. Bias supply 52, in this case an AC supply of sufficient frequency to pass current through the wafer 23, is connected to stage 51. Beam source supply 17 produces plasma 9. Without the bias supply 52, the insulating substrate 23 would normally rise to the characteristic floating voltage of plasma 9. (This is between approximately -10 to -40 volts for the beam source 24 depending upon process conditions.) By turning on bias supply 52, the voltage drop across the plasma dark space between the plasma 9 and substrate 23 can be changed, positively or negatively, to a level required for the process. Because the substrate 23 is not an electrode in beam source 24, it can be separately biased.

FIG. 8 shows how two beam sources, 24 and 24a can be applied to a generate a large area uniform plasma over a substrate. In this case the substrate is a flexible web 23 drawn over roll 64. The two beam sources 24 and 24a are identical except magnets 60 and 61 of source 24a (and the end magnets in this source not shown) arrange their south pole facing in toward the plasma 9 while source 24 has magnet 62 and 63 north poles facing inward. This configuration creates a sharing of magnetic fields between the sources and produces the closed plasma region 9 as shown.

FIG. 9 shows a section view of a PBS configured for a space propulsion application. The basic components of a magnetron electron source and cusp magnetic field are the same as in earlier figures. In this source the magnetic cusp fields 18 and 19 are created by electro-magnets 70 and 71. The electron source magnetron plasma 8 is created within the liner tube 16. Note that this source is round in shape and symmetrical on a centerline. The propellant gas is passed through cover 5 voids 72 before entering the source near plasma region 39. In operation, electrons created by magnetron plasma 8 are trapped in mirror field region of magnetic field 18 and plasma 39 and 9 are created. Thrust is generated as the plasma 9 is expelled through nozzle 6. Note that by increasing the magnetic field strength in the region of nozzle 6, ions can be partially confined and heated by the radial electric field as they pass through nozzle 6.

FIG. 10 shows another variation on the beam source. As described earlier, this source can be circular, annular or extended length wise. The variations include the use of rare earth magnets 1 and 2 and the use of two power supplies 83 and 84. As shown, power supply 83 connects cathode liner 16 to box 3. Insulator 81 separates box 3 electrically from cover 5. Power supply 84 connects anode cover 5 to box 3. Box three is grounded. Using this configuration, the plasma potential can be adjusted relative to ground. This can be useful when applying the plasma 9 to a grounded substrate. By raising the plasma potential the ion energy striking the substrate can be increased. FIG. 10 also shows process gas manifolds 80 built into cover 5. Small distribution holes 85 conduct the gas uniformly along the source into plasma region 39.

The present invention opens the doors to improving many applications and processes. Several have been mentioned above. Many more will be apparent to those skilled in the art. While several configurations have been shown, many more are possible. The basic idea of the present invention is to use an internal magnetron cathode as an electron source to feed a mirror electron containment plasma source. Once a basic understanding of this method

is understood, many devices implementing this useful combination will be evident. Some of the possible variations are:

- The plasma beam source can be made annular. The Helmer patent shows how this can be done with the hollow cathode sputter source.
- The magnets can be turned to face upward similar again to the Helmer patent (5,482,611). This arrangement is also similar to a Type II unbalanced magnetron (Window and Savvides, 1985). When this is done the cusp field is pushed out farther toward the substrate. If cover 5 is opened such that nozzle 6 is a large opening, or cover 5 is simply the vacuum chamber walls, a plasma beam is still formed but, as is described by Helmer, exposing the magnetron to the vacuum chamber greatly increases sputter material ejection from the source. The present invention can still use this magnet configuration by fitting a narrow nozzle over the unbalanced magnetron or hollow cathode source.
- The beam source can be made non-planar in any axis, that is it can be twisted or curved into a shape to say, conform to a particular substrate requirement.
- The center shunt 10 is not required. While preferred because less sputtering of liner 16 occurs when shunt 10 is present, it is not necessary.
- Nozzle 6 and cover 5 can take on a variety of forms. Depending upon the level of sputtered material tolerable to the plasma process, nozzle 6 can be fully removed and cover 5 can be opened to expose liner 16 to the process.

CLAIMS

I claim:

1. A magnetron cathode electron source feeding a mirror confinement plasma source producing a beam of plasma for non-sputtering applications such as PECVD, plasma treatment, reactive ion etching or space propulsion applications..

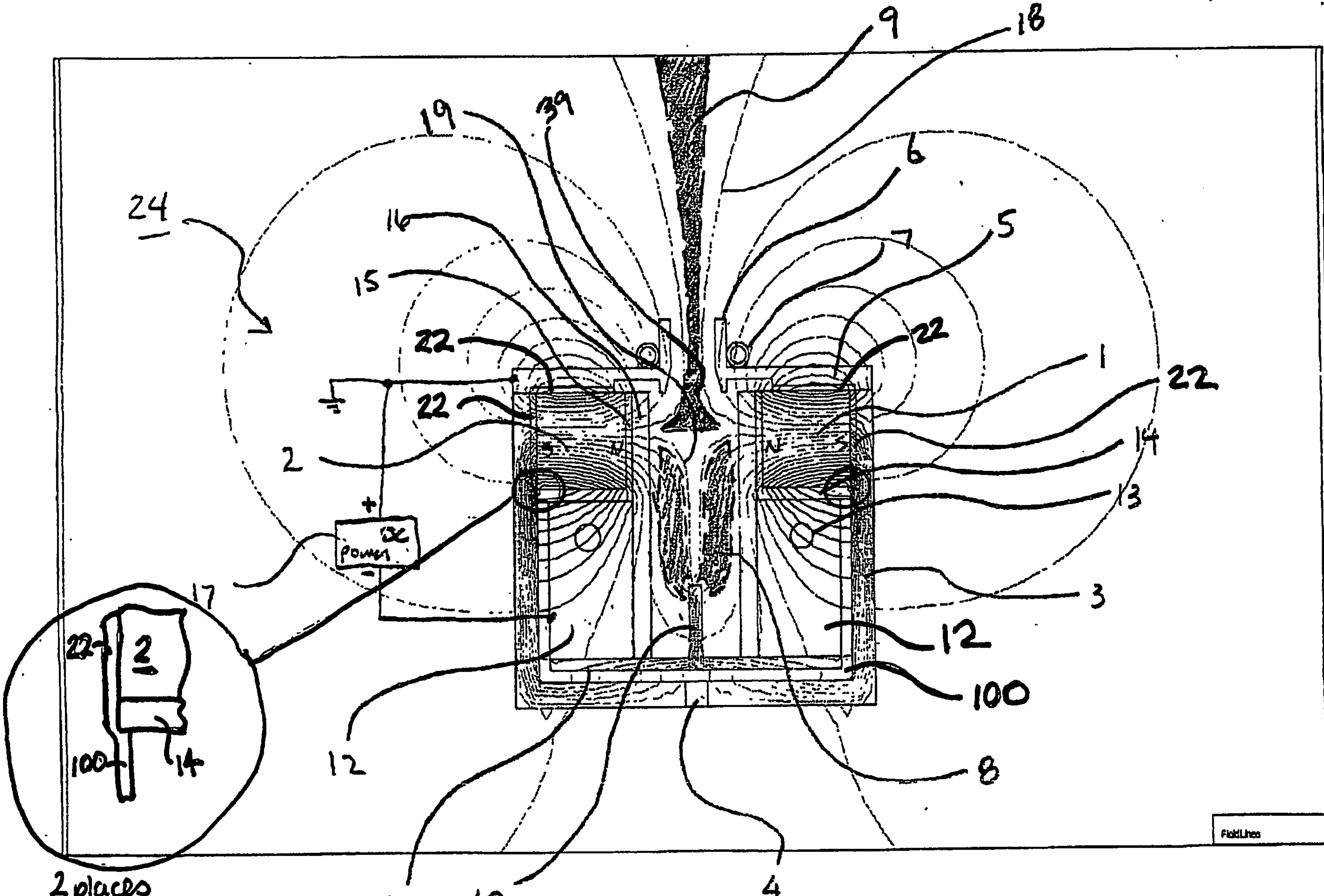

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FIG 1

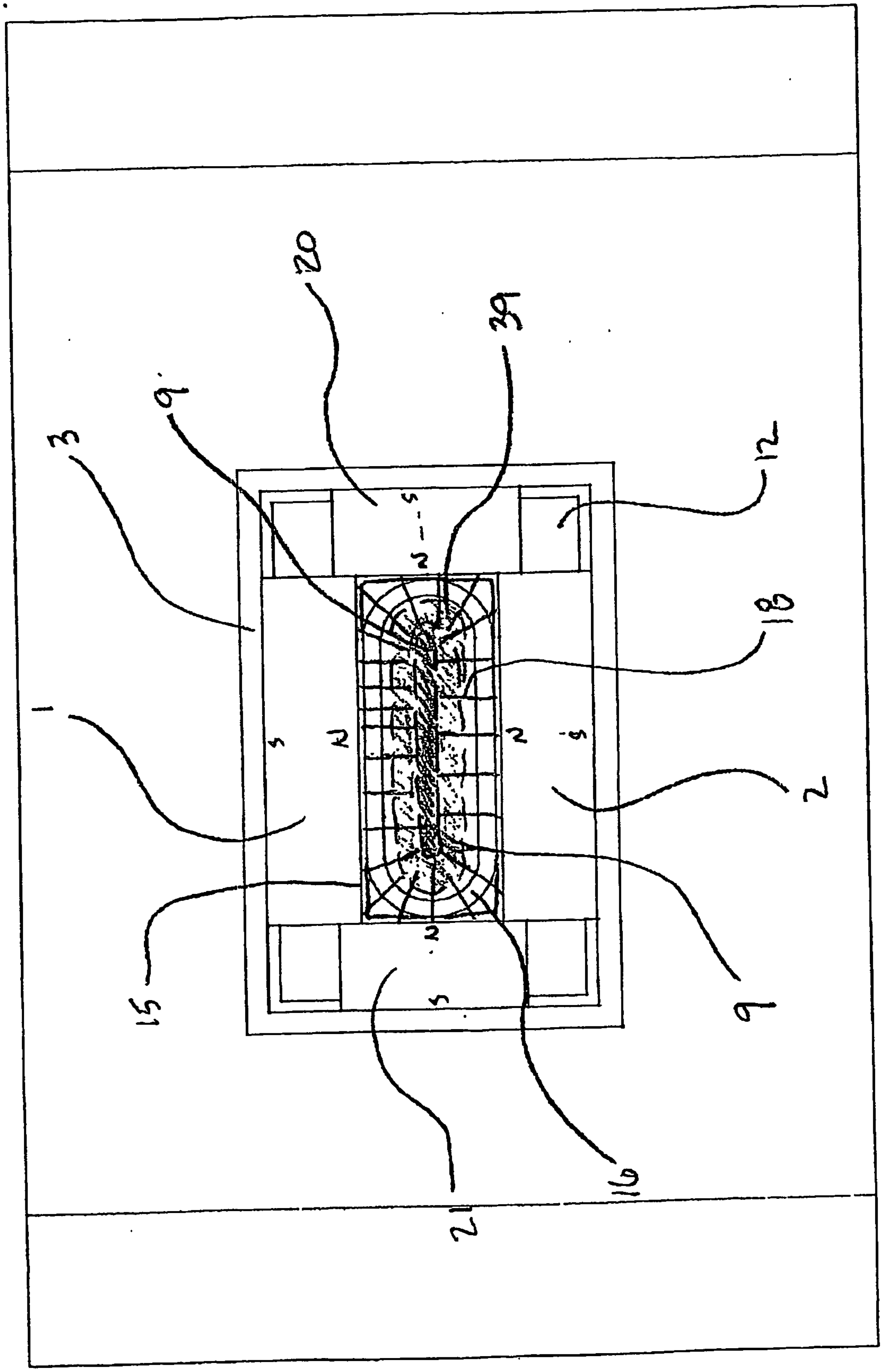

FIG 2

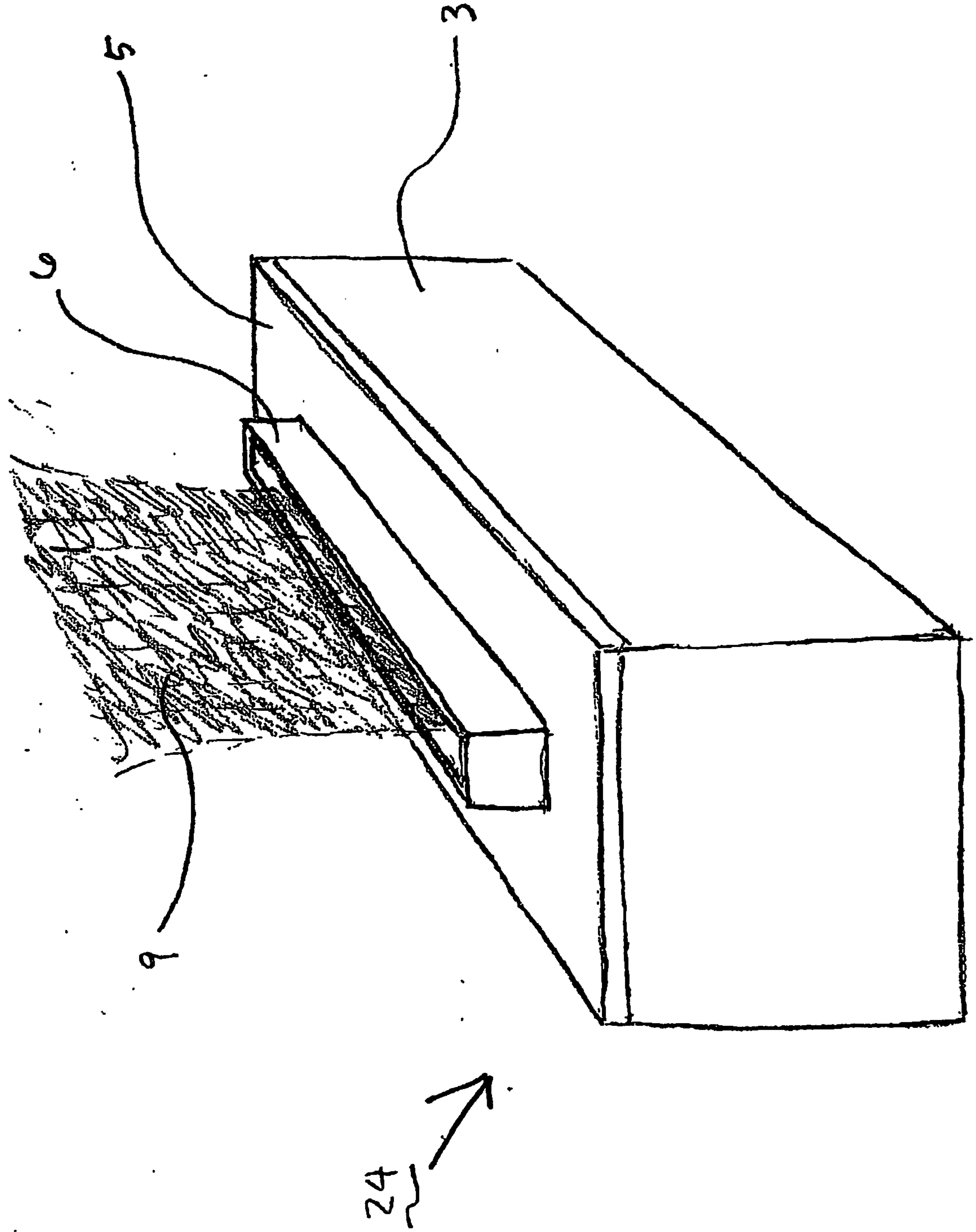

FIG 3

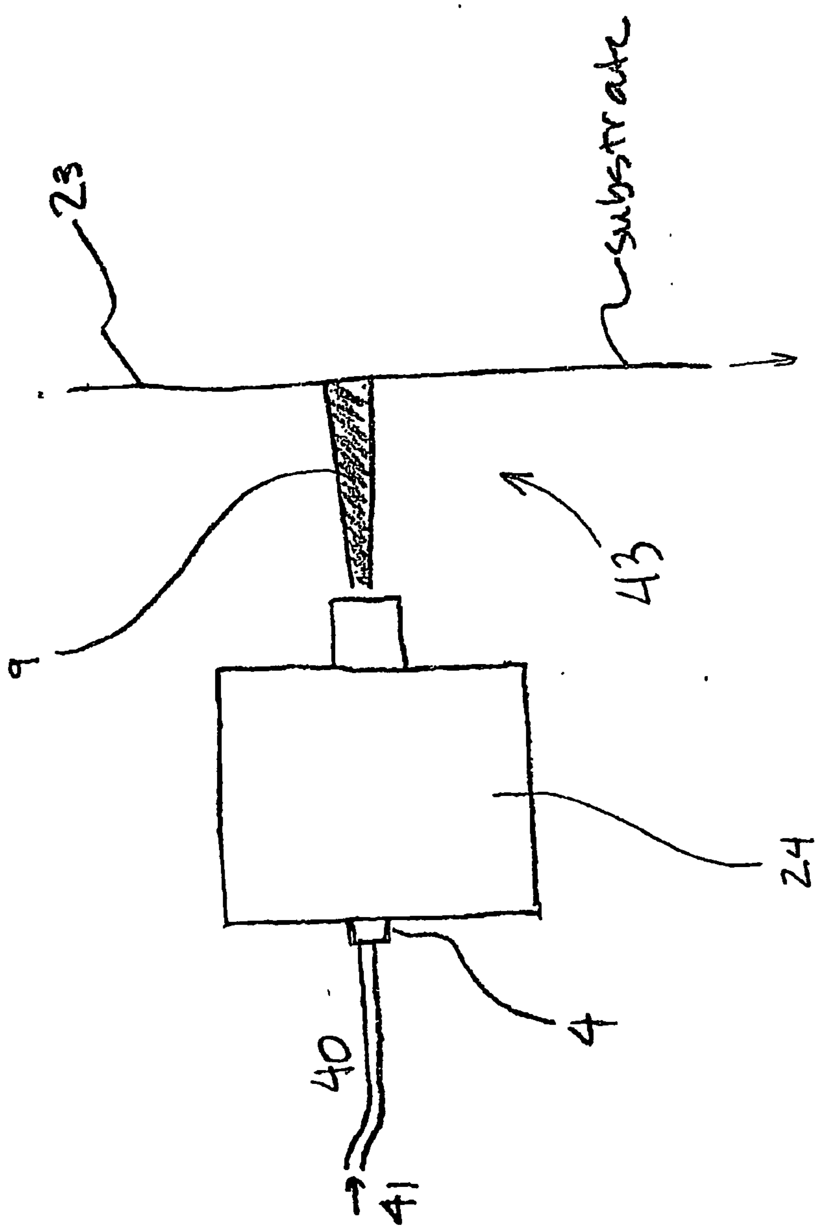

FIG 4

Atty Docket No. 1063078

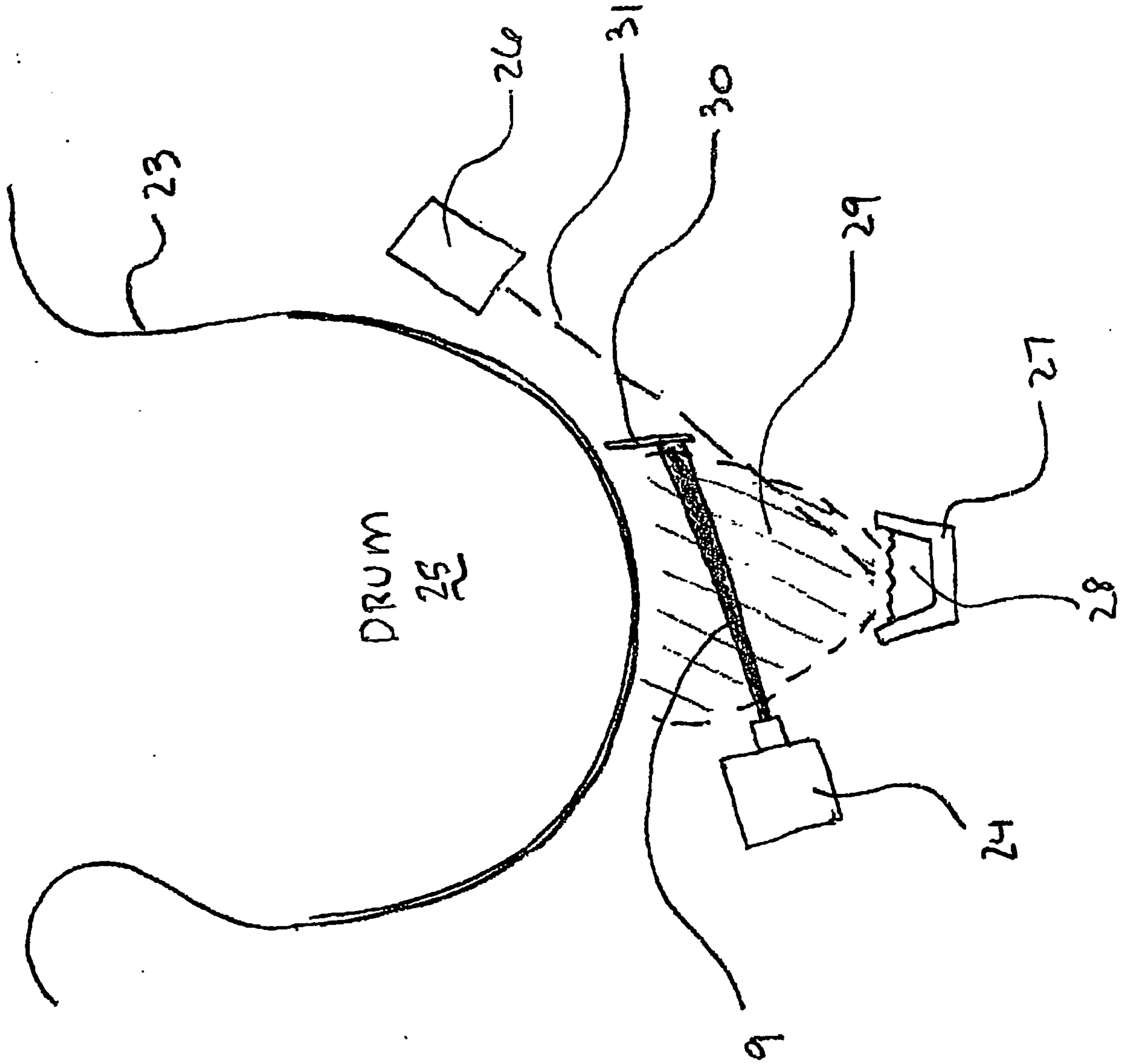

FIG 5

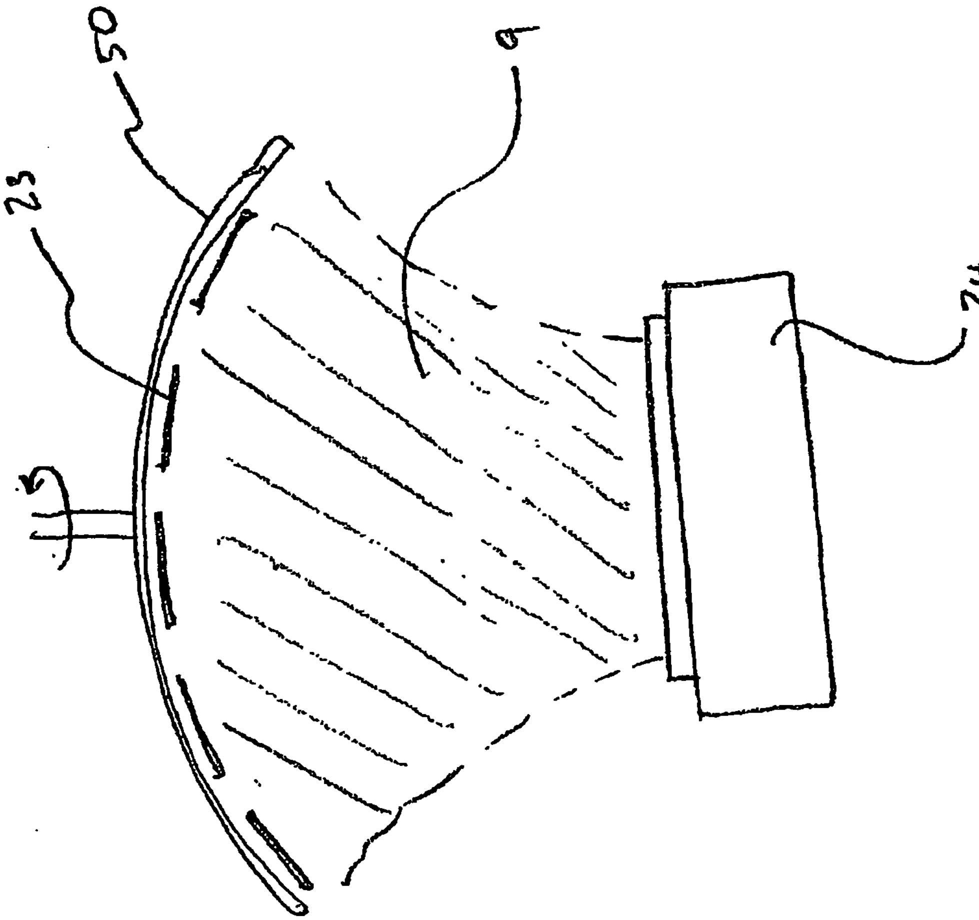

FIG 6

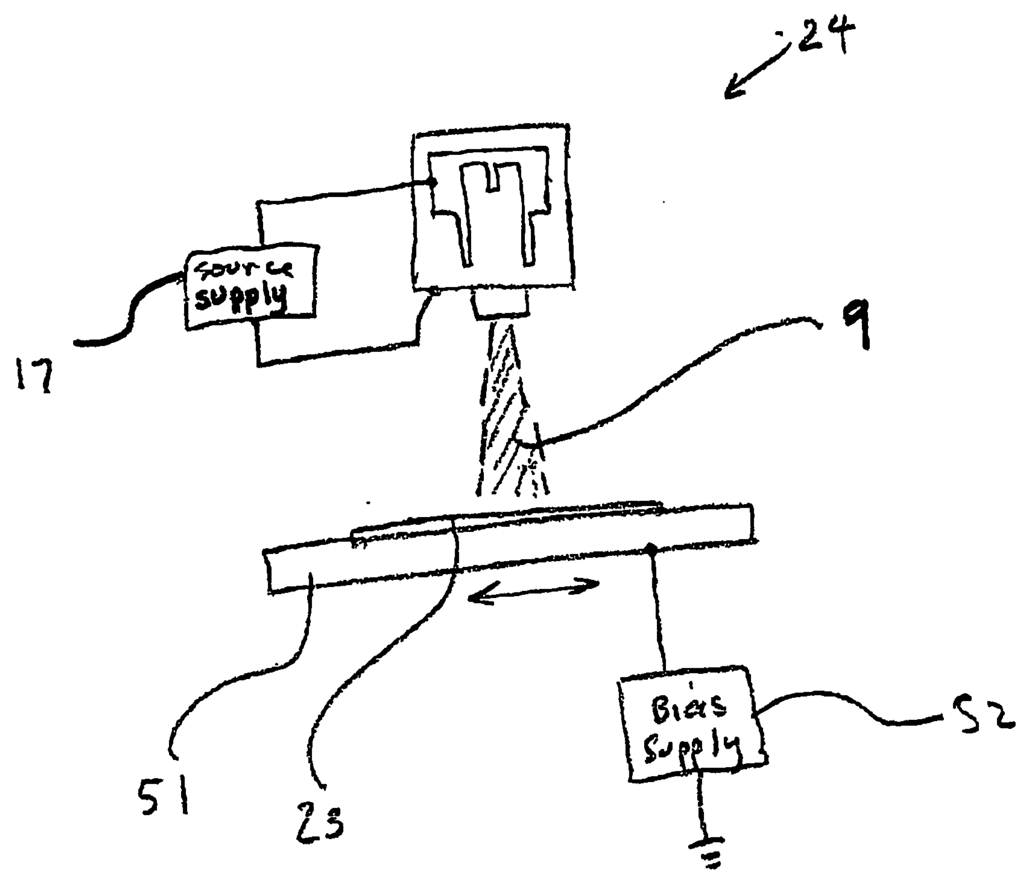

FIG 7

Atty Docket No. 10630-18

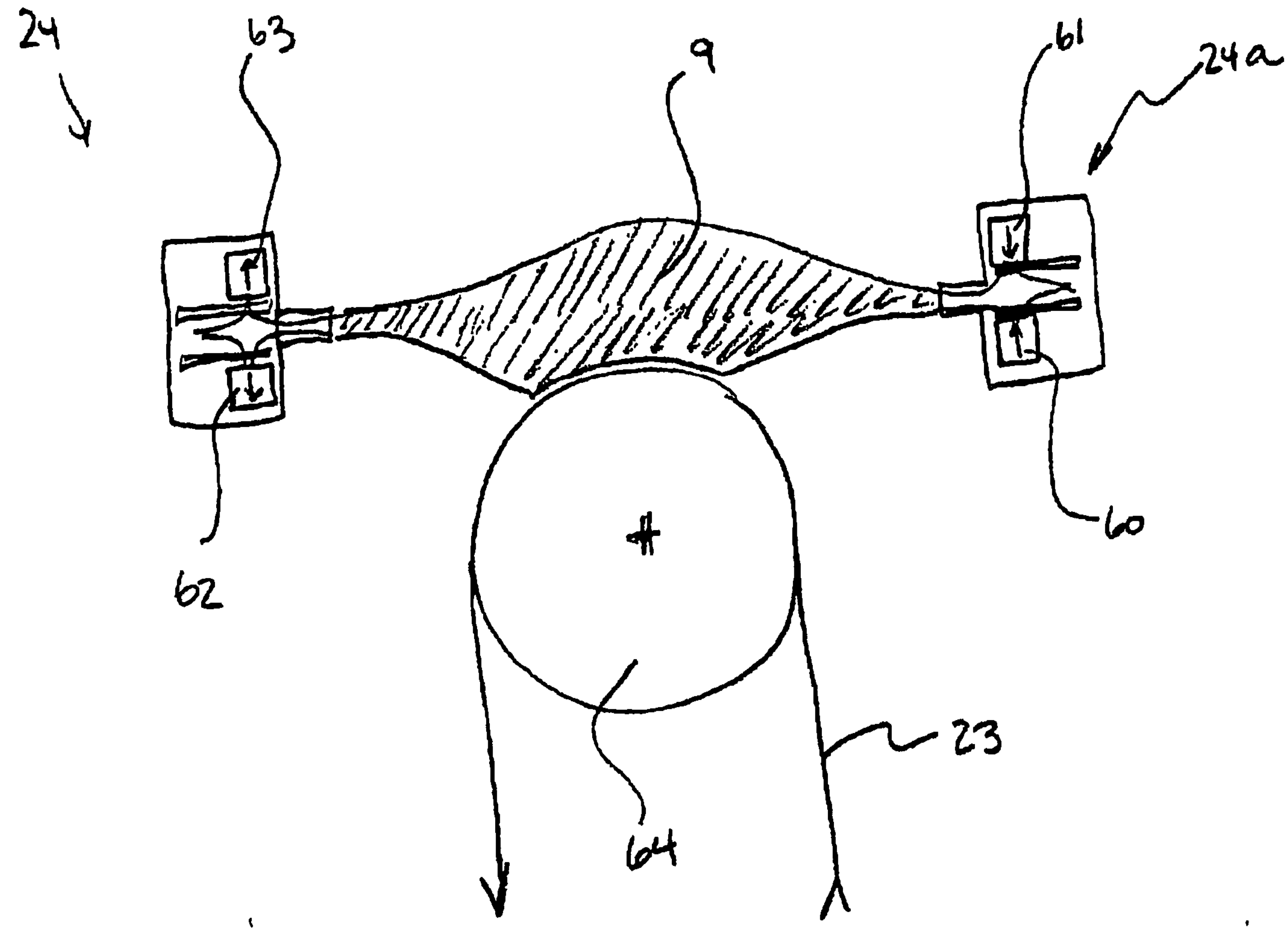

FIGURE 8

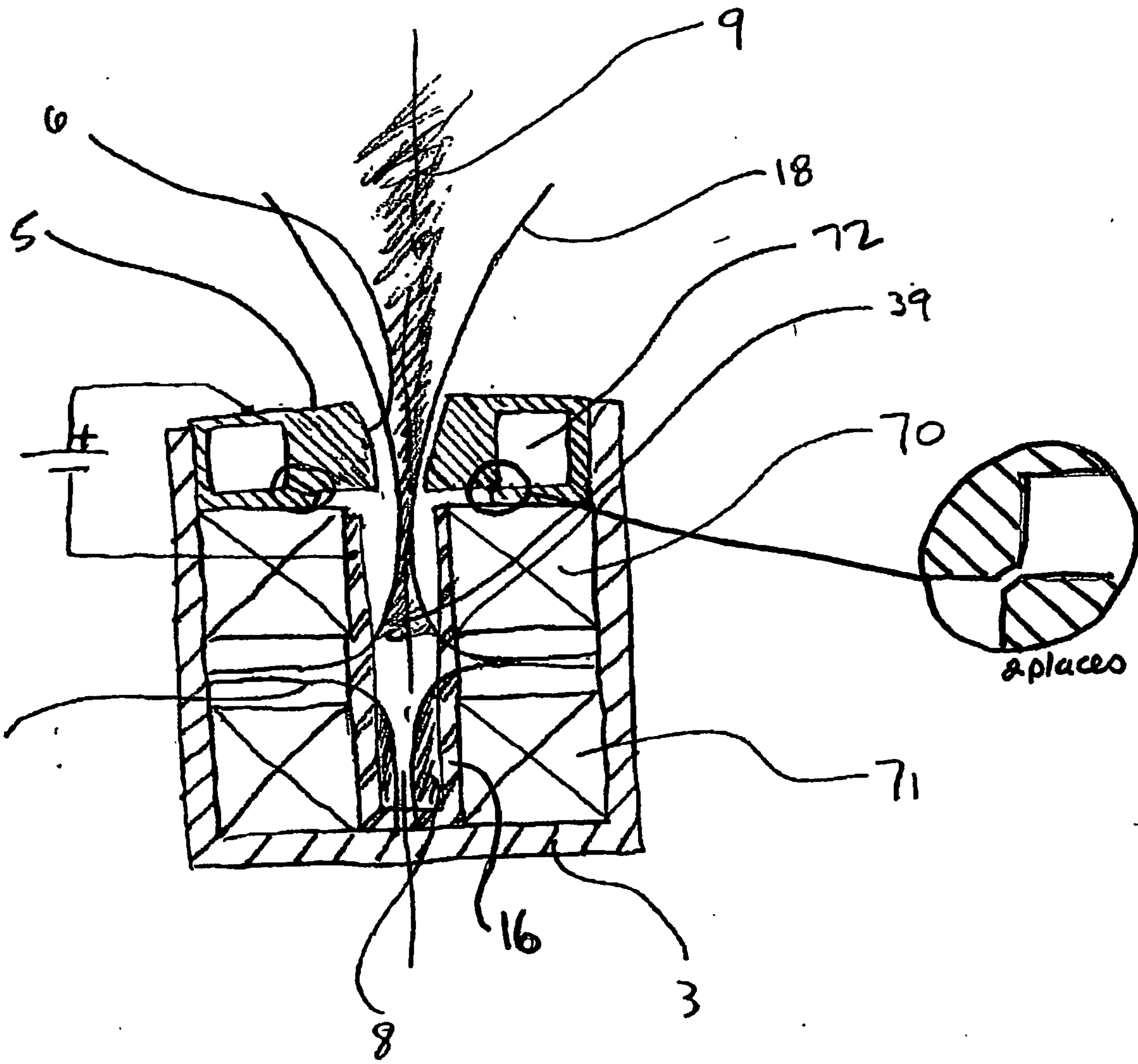

FIG 9

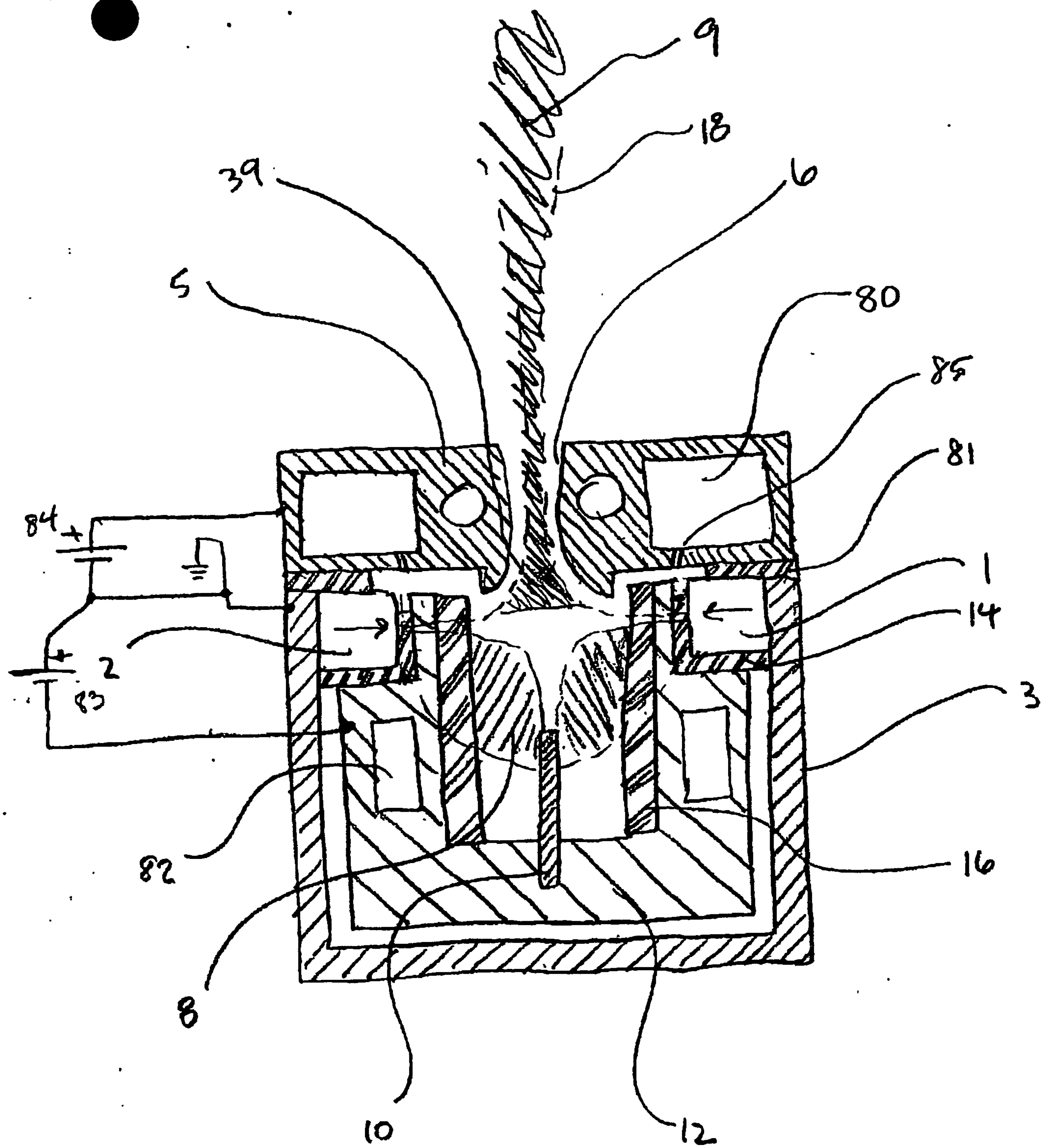

FIG 10

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